Brain Neuromodulation Effects on Sport and Nutrition: A Narrative Review

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Abstract

Study purpose. At the end of the twentieth century, the development of highly reliable and painless non-invasive transcranial brain stimulation techniques and devices has aroused great scientific and clinical interest in numerous fields. In neuroscience, since the introduction of innovative and non-invasive devices such as the brain stimulator, the investigation of cortical processes and their neural basis has played a fundamental role. Furthermore, neuroscientists are attracted to therapeutic applications for the treatment of food craving. This narrative review is aimed to explain the growing and constant interest of neuroscientific experimentation in the field of non-invasive transcranial stimulation.

Material and methods. After an introduction explaining the historical evolution of NIBS, we will try to provide an overview of the two stimulation techniques (TMS and tDCS); we will describe the different types of stimulation that can be performed using these techniques, the excitatory/inhibitory effects, and the various mechanisms of action at the level of brain activity.

Results. We will also provide some elucidations regarding the implications of the facilitative/inhibitory effects, and how these stimulation methods can be used to advance knowledge of the neurofunctional organization of the brain.

Conclusion. The results of the study showed the effect of brain neuromodulation on sports and nutrition.

Keywords: Non-Invasive Brain Stimulation (NIBS), Transcranial Magnetic Stimulation (TMS), Transcranial Direct Current Stimulation (tDCS), Cortical Excitability, food craving.

Introduction

The search for perfection in the fields of sports and nutrition is unrelenting (Forbes et al., 2022). Athletes and the teams that support them are constantly looking for new ways to improve their physical capabilities, streamline their training schedules, and sharpen their minds (Shaw et al., 2022). In the midst of this never-ending quest for top performance, the fascinating field of brain stimulation has become a potent weapon in the athlete's toolbox (Forbes et al., 2022). Brain stimulation techniques have shown the ability to revolutionize sports performance and nutrition practices, from honing cognitive skills to adjusting bodily responses. Brain stimulation refers to the use of various techniques and technologies to modulate or regulate the activity of the nervous system, particularly the brain. It involves the application of electrical, magnetic, chemical, or other forms of stimulation to specific neural pathways or regions to influence their function (Antal et al., 2022a). The brain stimulation has a wide range of applications in medicine, research, and even some emerging applications in non-medical contexts. Neuromodulation is being explored for a variety of emerging applications, including...
enhancing athletic performance, improving sleep quality, treating addiction, and even as a potential therapy for neurodegenerative diseases (Van Ophoven, 2023). The use of brain neuromodulation in the context of sports and nutrition involves the use of neuromodulation techniques, like transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) to optimize brain function and enhance different aspects of athletic performance, including cognitive function, motivation, and even appetite regulation (Kesikburun, 2022). In fact, neuromodulation techniques have been explored to enhance cognitive functions such as attention, memory, and decision-making. Athletes can use these techniques to sharpen their mental acuity, which is critical for strategic planning and focus during training and competition. Moreover, considering that the brain plays a central role in regulating appetite and food intake, these techniques could be investigated for their ability to influence appetite control, potentially assisting athletes in managing their dietary choices and body weight for optimal performance. Furthermore, brain stimulation techniques have demonstrated effects on stress, cognitive improvement, motivation, mental toughness and appetite regulation, all fundamental aspects for both sport and nutrition (Barwood et al., 2016; Dumel et al., 2018; Edwards et al., 2017; Hazime et al., 2017; Lattari et al., 2018; Wang et al., 2022).

Different non-invasive brain stimulation (NIBS) techniques affect neuronal states through different means. However, the stimulation of the human brain implies, as an essential element, that these methods can induce a variation in the membrane potential of neurons. The membrane potential is an electrical voltage, measurable in a difference between the inside and the outside of the neuron (Amassian et al., 1990). This difference is given by an imbalance of positive and negative electric charged with ions. In resting conditions, the membrane potential of a neuron remains stable, thanks to a precise distribution of ions between its interior and exterior (Matsumoto et al., 2013). However, neurons are dynamic entities, capable of undergoing substantial transient variations of the membrane potential which are the basis of the transmission of information, in particular through the generation of signals which take the name of action potentials (Groppa et al., 2012).

The different brain stimulation methods can modify the state of the neuron through electric currents and, consequently, favor the generation or otherwise of action potentials (Vidal-Dourado et al., 2014). TMS is mainly a neurostimulation method which involves the induction of a depolarization of the neuronal membranes and the initiation of action potentials in the stimulated area by means of an electromagnetic induction (Woods et al., 2016). The tES is neuromodulation technique that through low-intensity electrical stimulation, induces a variation in the state of the membrane potential, altering the ionic fluxes. This alteration can be a hyperpolarization or a depolarization of the neuron (Simonsmeier et al., 2018). The tES does not involve the direct induction of action potentials, but a variation of the response threshold of the stimulated neurons, with a consequent modulation of the response that the neuron will be able to provide.

Materials and methods

This narrative review tries to explain the brain neuromodulation effects on sport and nutrition. After an introduction explaining the historical evolution of NIBS, the present work tries to provide an overview of the two stimulation techniques (TMS and tDCS); describe the different types of stimulation that can be performed with these techniques, the excitatory/inhibitory effects and the various mechanisms of action at the level of brain activity. This work will also provide some elucidations regarding the implications of the facilitative/inhibitory effects, and how through these stimulation methods the knowledge of the neurofunctional organization of the brain can be broadened. Finally, it will explain the role of brain stimulation in physical exercise and nutrition. The bibliographic search was carried out on Pubmed using the following keywords: Non Invasive Brain Stimulation (NIBS), Transcranial Magnetic Stimulation (TMS), Transcranial Direct Current Stimulation (tDCS), Cortical Excitability, food craving, sport, nutrition.

Results

TMS

TMS is a non-invasive technique that allows to stimulate/inhibit or further modulate neural activity of cerebral cortex without solution of continuity. Its technical characteristics make it an important and promising tool for analyzing higher cognitive functions and the central motor pathway, making it possible to explore excitability, motor conduction and central motor conduction time. From the outset, the main source of interest in this technique has been the possibility of assessing the functionality of the corticospinal pathway in healthy subjects or subjects with neurological deficits in the motor sphere (Wagner et al., 2007). In this way, the propagation properties of the corticospinal fibers that control the target muscle can be examined in detail and the cortical representation of these muscles can be mapped, making TMS an effective technique for studying brain plasticity. Experiments show that an electric current flowing in a straight conductor generates a magnetic field around itself: it follows that a change in the magnetic field can in turn generate an induced current (Fregni & Pascual-Leone, 2007).

As far as magnetic phenomena are concerned, we can consider a magnet made up of two indivisible poles. This means that there are no positive or negative magnetic charges, and the very concept of magnetic pole is fictitious: magnetic forces are a manifestation of the motion of electric charges. The properties of a magnet do not depend on the presence of “magnetic charges” inside it but on the fact that it is traversed by electric currents. There are profound links between electrical and magnetic phenomena: the study of the reactions between these is the object of electromagnetism. Let us now consider a solenoid, formed by a wire wound in a cylindrical helix and traversed by an electric current. It creates output lines which are called magnetic flux (Rossi et al., 2021a).

Inside the solenoid, in the central region, the flux lines are parallel to the axis equidistant, and the magnetic field is uniform. Outside, however, the intensity is lower, the lines of flow are divergent, and the field is not uniform since the flow, going out, branches out by reducing its intensity with an index inversely proportional to the square of the distance. The magnetic flux is measured in weber (Wb) while induction, which expresses the distribution of the lines of force in space, is expressed in the head which corresponds to weber/metre$^2$. 

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In summary, an electric current can generate a magnetic field and at the same time a variation of the magnetic field can generate an induced current. By applying these observations to the neurophysiological field, it can be understood that a rapid variation of a magnetic field applied to an area of the human body can cause the current to originate in its, and therefore it causes a stimulation. This observation is underpinning the development of magnetic stimulation. The magnetic impulse comes generated by the passage of current in the coil. This pulse induces a current in an electrically conductive area, such as the human body. If the current has sufficient amplitude and duration, it is possible to stimulate the neuromuscular tissues in the same way as more conventional electrical stimulation (George et al., 2002). The safety level is today guaranteed because the TMS device has a capacitor which loads and unloads (Rossi et al., 2021b). Using the charger circuit, the energy stored in the capacitor is discharged to one level pre-determined in the front control panel up to a maximum of 2.8 kV. When the stimulator receives a trigger signal as input, the energy stored in the capacitor is discharged into the stimulator coil (Zhang et al., 2022). In a few milliseconds the discharge switch can develop large currents. The switch is constructed in such a way to conduct the current in a precise direction and therefore the stimulator produces a monophasic current discharge with no reverse current. The possibility of reducing heat dispersion in the coil is linked to the monophasic discharge. The coil consists of a flat circular coil in which a variable current flows capable of providing a magnetic field (de Goede et al., 2018). Over the years, different application of TMS have been proposed and tested: single-pulse (spTMS), paired-pulse (ppTMS), repetitive (rTMS) and pattern stimulations such as theta bursts (Rossini et al., 2015). The first devices capable of delivering only a single pulse found widespread use in the clinical field in the evaluation of specific neurophysiological parameters: for example, the inaudible response in a peripheral muscle after having detected the primary motor cortex (M1), in order to evaluate the clinical status of the pathway which, from the cortex, carries the signal to the peripheral muscles, generating the motor evoked potential (MEP) (Moscatelli et al., 2017; Jameson, 2023). In the experimental investigations, single pulse stimulations immediately found widespread use in the field of neuroscience, to evaluate the role of a brain area in a specific function of interest. The first technological developments in the field of TMS led to the development of protocols which envisaged the use of ppTMS. These protocols provided for a conditioned stimulus (CS) followed by a test stimulus (TS), allow us to evaluate how two areas are connected to each other, through the induction of cortical facilitation or inhibition phenomena. In particular, they evaluate how MEP amplitudes can be modified on the basis of the interstimulus interval between CS and TS or on the basis of the subject’s status (Rossi et al., 2001; Veniero et al., 2012). In numerous protocols, the experiment involves the use of a range of intensities of the CS to induce inhibition or facilitation (starting from values below the threshold, up to values above the threshold). The intensity of the TS is usually set at 110-120% of the central motor threshold. When the two stimuli are administered in two different areas, these protocols provide important information on the degree of connection between the two areas (i.e. cortical connectivity). At the beginning of the 90s, devices capable of administering different stimuli (defined trains of stimuli) in rapid succession (rTMS) were introduced, which allowed the use of this method also in other research area. If applied as a single pulse, the induced current has sufficient amplitude to depolarize neurons (neuro-stimulation). If applied repeatedly at various frequencies and for a few milliseconds, rTMS modulates cortical excitability, decreasing or increasing it. The modulatory effect of rTMS lasts longer than the stimulation period, generally at least as long as half of the stimulation period. Much of the research investigating the effects of rTMS on cortical activity has focused on the effects of motor area stimulation, as the excitability of this brain region can be easily measured with MEPs (Moscatelli et al., 2020; Moscatelli et al., 2016). There is a large consensus in the literature that the application of low-frequency (LF) rTMS trains, below 1 Hz, induces mainly inhibitory effects, while high-frequency (HF) stimulations, above 5Hz and up to 25 Hz, induce facilitative effects (Moscatelli et al., 2023). TMS follows the rules of logical inference: if cortical area “A” is involved in cognitive process “X”, and is not involved in process “Y”, the alteration of the activity of area “A” will lead to an impaired performance in “X” and not in “Y” (Antal et al., 2022b). By deductive reasoning, area “A” plays a causal role in process “X” (Bortoletto et al., 2021). The functional impact of TMS essentially depends on its ability to transiently influence neuronal activity, modulating the information processing, based on the state of the stimulated area. The TMS offers the advantage of indicating, along a time continuum, when a specific cognitive event occurs. In this case, the stimulation method is spTMS, because it exploits the high temporal resolution of the magnetic pulse, which is in the order of milliseconds (Lefaucheur et al., 2020). These methods are useful not only to limit the temporal activation field of a given brain area, but also to highlight the different role that the airways play in the different moments of sensory and cognitive processing (Jannati et al., 2023). However, rTMS protocols also offer the possibility of defining precise time windows. Initially, the stimulation can be applied over a large time interval (about 500 ms), just to see if it is possible to interact with the execution of the task by stimulating a given area (Lefaucheur et al., 2014). Once the involvement of this area has been established in a given time window, it is possible to reduce the stimulation time by increasingly narrowing the window (Perinelli et al., 2019). Therefore TMS, applied according to specific experimental paradigms which mainly aim at identifying the moment in which an area comes into play in a cognitive process, can identify circumscribed temporal windows of information processing. In this case, it should be noted that the effects induced by spTMS, but also by on-line rTMS, are generally short-lived, i.e., approximately a few hundred milliseconds. The case of the long-term neuromodulation effects of rTMS applied in protocols defined off-line, i.e., before the execution of the task, or those resulting from the repeated application of rTMS is different. In the online application, the longer the stimulation period and the higher the rTMS frequency, the greater the interference on the activity of the stimulated brain region and the final effects, observable in the subject’s behaviors (Savino et al., 2023). However, there is an increased risk of inducing non-specific behavioral effects, which can make the results more difficult to interpret. In these cases, the use of a TMS called sham, or ineffective/
placebo stimulation, is used. During sham stimulation a TMS is simulated, but no magnetic field reaches the underlying cortex. The simplest way is to interpose a non-conductive material 3 cm thick between the coil and the scalp, alternatively you can rotate the coil by 180° (Rossi et al., 2021b). As there are multiple brain regions that may be involved in exercise regulation, the rationale for using brain stimulation for performance enhancement and the regulation of food intake, may vary accordingly, which may provide an explanation for the inconsistent results of different studies (Machado et al., 2019). It seemed that different stimulation conditions and parameters may contribute to different results (Bastani & Jaberzadeh, 2012). Moreover, warm up or training exercises conducted simultaneously with NIBS have been adopted in a few previous studies, which may be a factor to influence the results (Park et al., 2019).

rTMS

The rTMS is defined as the application of a train of pulses of the same intensity to a single brain area at a given frequency and intensity. In general, high frequency stimulation, is correlated to interference with cortical functions during the application of the pulse train. However, following these immediate effects, a train of rTMS pulses can also induce sustained modulation of cortical excitability which can persist well beyond the duration of the train itself (Amanda S Morrison, Andero Uusberg, 2022). The modulation effect can range from inhibition to facilitation based on the stimulation parameters used, as was the case for ppTMS. Lower frequencies, for example 1 Hz, applied to the motor cortex can repress its excitability, while stimulation trains at higher frequencies, around 20 Hz, lead to an increase of cortical excitability. These effects vary depending on the individual considered and the shape of the trains, however in general the low frequencies (around 1 Hz) produce very long-lasting and robust effects and can therefore be applied to the motor cortex and other cortical regions to study the behavioral relationships of the brain (Gornerova et al., 2023). To obtain an even more persistent and important effect in the neuromodulation of the chosen area, various stimulation frequencies are usually combined. It should be emphasized for regarding the limits mentioned above, that they are not entirely arbitrary. It is in fact known, for example, that low frequencies around 1Hz can be correlated to depression or long-term potentiation following tetanic nerve stimulation: there is evidence that demonstrates that rTMS at high and low frequencies identified above produce relatively distinct both on direct measures of brain activity and behavior. Using rTMS therefore, frequency appears to be the key parameter determining the direction of effects, although other variables should be taken into consideration while planning an experiment with this method. For example, attention should be paid to the pulse train duration, the interval between two trains, the total number of trains and pulses in a session duration or over a given area. By respecting the parameters, two main ways of performing rTMS are defined: online and offline.

Transcranial Direct Current Stimulation (tDCS)

Transcranial Direct Current Stimulation (tDCS) is a non-invasive brain stimulation method able to induce functional changes in the cerebral cortex. The tDCS essentially consists in the application on the scalp of electrodes delivering a direct current of low intensity able to crossing the scalp and influencing neuronal functions, finding application in numerous clinical, diagnostic and research fields (Cabral et al., 2015; Lattari et al., 2016, 2020). If the study of the brain has always aroused great fascination in scientists since ancient times, the effects of the current on it have been objects of large scientific and non-scientific interest since its discovery in the world. In fact, the effects of uncontrolled brain stimulation have been reported since the past. Looking at the most recent history, the use of the therapy electroconvulsive and psychiatric drugs and the lack of reliable neurophysiological signals, obscured the use of direct current on the central nervous system as a therapeutic and research tool, especially in the field of psychiatry. However, galvanic current continued to be used without interruption in the treatment of musculoskeletal disorders and peripheral pain in the meantime. These first efforts in the neurophysiological field, therefore, were probably abandoned due to lack of reliable evaluation methods. When in 1998 it was possible to measure the effects of direct current application on the motor cortex non-invasively by means of transcranial magnetic stimulation, tDCS became reliable in terms of parameters such as stimulation intensity, duration and validation of its following plastic effects (Al-Tawarah et al., 2022).

From a technological point of view, the tDCS instrumentation has a rather simple structure compared to other stimulation devices. In fact, it is mainly composed of two electrodes and a battery device capable of supplying a constant flow of current in a continuous manner. These basic components can be connected to other components, such as for example a software that offers the opportunity to choosing between different stimulation protocol or multiple-session experiments. Naturally, since they must create a closed circuit once in operation, the two electrodes correspond to a cathode and an anode. By placing them over the scalp, it can be modulating a specific area of the central nervous system. The positioning of the electrodes therefore assumes a crucial role and is usually determined in line with the international system of EEG 10-20. For example, studies exploring the motor cortex place electrodes above zone C3 and C4. The electrodes used are usually sponge and the surfaces range from 25 to 35 square, but they can change in order of size. To create the homogeneous electric field responsible for the plastic effects of the neural tissue, and therefore necessary for tissue analysis, a direct current is usually made to flow inside the electrodes which can vary from 0.5 to 2 mA, for about 20-40 minutes. It can induce even lasting changes in the brain, both excitatory and inhibitory, while remaining subthreshold. This neuromodulation technique consequently provides a practical and less invasive alternative to, for example, direct stimulation. In fact, tDCS can be used in general to manipulate brain excitability by means of polarization membrane: a cathodal stimulation hyperpolarizes, an anodal stimulation depolarizes the resting membrane potential. In this regard, it should be specified that the current flow in question is a flow of ions present in the brain tissue. Therefore, the positive ions will tend to flow towards the cathode, while the negative ones will flow towards the anode. The flow comes conventionally considered directed from the
anode towards the cathode, creating as mentioned a closed circuit in which the current passes through the head. There are two main types of assembly for electrodes, but different nomenclature to define them. Therefore, for the sake of clarity, it is now necessary to discuss some terms used to describe the assembly of tDCS. When an electrode is placed under the neck, the entire assembly is referred to as “unipolar”. Conversely, montages with the two electrodes on the head are usually referred to as “bipolar”. This nomenclature, however, could be considered technically inaccurate, since DC stimulation is always generated by means of two poles (electrodes) which generate an electric dipole between the two electrodes. Therefore, an alternative nomenclature to use could be that of “monoencephalic” and “biencephalic” to differentiate the “unipolar” and “bipolar” set ups respectively. Researchers in the field also use the terms “reference” and “stimulation” electrode to refer to the electrode respectively neutral and active with respect to the area to be investigated. However, even the term “reference” can be problematic especially for the biencephalic montage because the reference electrode is not physiologically inert and can contribute to the modulation of activity as the active one (Woods et al., 2016). This could be a potential confounding factor. Nevertheless, the researchers use this term to underline that, in their studies, they assume that in their assembly one electrode will be considered for stimulation, while the other as reference.

**Sport and brain stimulation**

The brain stimulation is thought to have ergogenic potential for increasing muscular strength and stamina in both athletes and non-athletes (Goodall et al., 2014; Lattari et al., 2020; Moscatelli et al., 2023). The left dorsolateral prefrontal cortex (DLPFC) is the region that is most frequently targeted in studies of NIBS and sport because it controls the inhibition of motor regions. In general, this region plays a part in the modulation of many different processes and functions, including emotion, mood, and memory. Consequently, it is challenging to gauge the effect of a specific stimulus on just one metric (Karlinsky et al., 2017). One of the most crucial areas in determining whether or not to continue exercising is the left DLPFC since it controls exertion and weariness (Monda, Salerno, et al., 2017a). Physical exhaustion is a complicated process that may be influenced by elements like cerebral inhibition and perceived effort. EEG measurements of brain activity (beta power) during exhaustion show an increase along with a stronger synchronization between the left and right DLPFC (Antal et al., 2022a). When central tiredness brought on by exercise occurs and motor cortical activation declines, fatigue may be compensated in the DLPFC. Accordingly, Lattari et al. (2020) discovered that anodal tDCS applied to the left DLPFC and cathode over the Fp2 at 2 mA for 20 min improved volume load and perceived exertion in comparison to sham tDCS and tDCS employing a reversed montage for lower limb activity in healthy young people (Maldonato et al., 2018). In comparison to sham stimulation, 20 minutes of anodal tDCS at 2 mA delivered over the left DLPFC (cathode over the Fp2) enhanced the tolerance to the maximal load exercise conducted in the cycloergometer in moderately active women. This study suggests that by preserving the volitional impulse to the motor cortex, altering the neuronal activity in the left DLPFC may improve endurance exercise performance. However, other investigations have not been able to demonstrate any discernible effects of tDCS on exercise performance (Barwood et al., 2016; Monda, Salerno, et al., 2017b; Polito et al., 2020). Recent studies on the improvement of jump performance have confirmed earlier studies on the facilitation of motor learning (Antal et al., 2022b). The possibility of enhancing gross motor power or endurance may be higher compared to the demands of skilled sports, if evidence on experienced musicians could be generalized to sports (Messina et al., 2015; Huang et al., 2009; Polito et al., 2019). An important review, 60% of the studies reported improvement in physical performance when a-tDCS was administered (Angius et al., 2018). More specifically to the type of exercise performed, 62% of the studies involving whole-body exercise reported an improvement in physical, with similar benefits for single-joint exercise (60%). Additionally, 60% studies investigating endurance (both in whole body and single joint exercise) found improvement in performance, while 57% of the studies have found improvement in strength, power, or anaerobic work capacity. However, the effects of tDCS on physical performances are highly variable. Authors suggested that the high inter-individual variability (i.e., responders vs non-responders) to NIBS and more specifically to tDCS could explain the variance in experimental outcomes (López-Alonso et al., 2015). In addition, the different electrode montages used and stimulation protocols could have surely contributed to mixed result. Likewise, due to differences in electrode size and position, as well as to the relatively low focality of induced electric field (Miranda et al., 2013), other brain areas beyond the targeted one could be affected by tDCS and profoundly affect the experimental outcomes. Overall, tDCS seems to improve endurance, strength, power and anaerobic capacity. Taken together, the currently available literature provides interesting insights about the potential for tDCS to enhance physical performance.

**NIBS and eating behavior**

The first study on non-invasive neuromodulation’s use for controlling eating behavior was conducted in 2005 (Uher et al., 2005). The only methods that have been applied in this situation are TMS and tDCS. The targeted region of the brain is the complex DLPFC, which facilitates cognitive control of food intake and is associated with executive processes. The fundamental assumption is that increasing DLPFC activity may change the reward–cognition balance in a way that facilitates cognitive control and may even decrease reward-related systems that cause overeating and food cravings. It is still completely unknown which specific DLPFC-dependent cognitive functions are impacted by rTMS or tDCS and how this influences the reported behavioral effects. Changes in reward valuation mechanisms, attentional biases, or inhibitory control are a few possibilities (Messina et al., 2018; Moscatelli, Sessa, et al., 2021; Valenzano et al., 2019; Val-Laillet et al., 2015; Viggiano et al., 2010). Only the left DLPFC has been the subject of rTMS investigations using excitatory protocols (10 and 20 Hz). Both the right and left DLPFC in a-studies have been the target of tDCS investigations, however with slightly different approaches/montages. The majority
of research have examined the effects on food seeking, perceived hunger, and food intake (all with tDCS, one with rTMS). Overall, they have consistently discovered a severe suppression of appetite and self-reported food cravings on ratings or visual analogue scales (VAS). There is some evidence that the tDCS impact may be more focused on sugar cravings (Esposito et al., 2016; Minervini et al., 2023; Monda, Nigro, et al., 2017).

The findings of these preliminary investigations offer a strong proof of concept for the application of non-invasive neuromodulation to the study of eating behavior (Messina et al., 2018). Potential applications include rebalancing ventral and dorsal brain systems or improving control and underlying brain regions to support successful weight loss maintenance in obesity (Bonni et al., 2023; Moscatelli, Messina, et al., 2021; Sperandeo et al., 2018; Val-Laillet et al., 2015; Yao et al., 2023). The general justification for employing noninvasive neuromodulation in the treatment of obesity and eating disorders is pretty evident, but the specifics are still being researched, and the optimum methods and protocols have not yet been established. To produce synergistic results, noninvasive neuromodulation can be utilized alone or in combination with other approaches like behavioral treatment, cognitive training, physical fitness, and diet.

Over the past decade, there is an increasing interest to use brain stimulation as a novel treatment approach for obesity and eating disorders (Ester & Kullmann, 2022). It is evident that multisession studies are more effective to reduce food craving and consumption than single-session approaches (Chen et al., 2020; Song et al., 2019). Moreover, results from various studies suggest that brain stimulation has a positive impact on food craving, particularly for specific foods such as sweets. Most trials were conducted with very limited sample size, which makes it difficult to draw firm conclusions. Yet overall, the literature on tDCS effects on food intake and craving display a mix of positive and null findings. In addition, the exact mechanisms behind tDCS effects remain unclear. Further research should focus on a combination of neuroimaging techniques such as fMRI and tDCS in order to provide underlying mechanisms of anodal and cathodal stimulation. The fast growing literature in brain research elucidated that brain regions do not operate in isolation but interact constantly with each other (Siegel et al., 2015). Multifocal tDCS targeting a whole network increases excitability in the targeted brain area more than twofold over time compared to conventional tDCS (Fischer et al., 2017). Therefore, multifocal tDCS arrangements with smaller electrodes could facilitate to stimulate whole brain networks and thus not only target the DLPFC but indirectly stimulate other brain structures involved in eating behavior regulation (Cotoia et al., 2018).

Discussion

The integration of brain neuromodulation techniques into the realms of sports and nutrition represents a fascinating intersection of science, performance optimization, and human potential. This narrative review explores the multifaceted impact of neuromodulation on athletes’ physical abilities, cognitive functions, and nutritional behaviors. One of the most prominent applications of brain neuromodulation in sports is its potential to enhance cognitive functions critical for peak performance (Moscatelli et al., 2023). Techniques such as transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS) have shown promise in improving attention, decision-making, and memory. These cognitive enhancements can be particularly beneficial for athletes engaged in sports demanding split-second reactions, strategic planning, and complex problem-solving. However, it is essential to note the variability in individual responses and the need for personalized protocols. Athletes seeking cognitive enhancements should approach neuromodulation cautiously, under professional guidance, and with careful consideration of ethical concerns surrounding performance enhancement. Beyond sports performance, neuromodulation also extends its reach into the domain of nutrition. The ability to influence appetite regulation through brain stimulation may aid athletes in managing dietary choices, body weight, and overall nutritional strategies (Ciliberti et al., 2018; Monda et al., 2017). This can have profound implications for athletes who need to balance their energy intake and expenditure for optimal performance. However, the complexities of appetite regulation and the individual variability in responses underscore the need for continued research. Ethical considerations also loom large, especially regarding the potential misuse of neuromodulation for unhealthy dietary practices or body image concerns. The application of brain neuromodulation in sports and nutrition is a dynamic field, marked by promising possibilities and ethical dilemmas. As this technology evolves, regulatory bodies, sports organizations, and practitioners must collaborate to establish guidelines that balance performance enhancement with athlete safety and fairness. Research efforts should continue to elucidate the mechanisms, risks, and benefits associated with neuromodulation techniques in the sporting context.

Conflict of interest

The authors have any conflicts of interest to declare.

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Вплив нейромодуляції головного мозку на заняття спортом та харчування: описовий огляд

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; Д – підготовка рукопису; Е – збір коштів

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Мета дослідження. Наприкінці XX століття розробка високонадійних і безболісних неінвазивних методів і пристроїв транскраніальної стимуляції головного мозку викликала значний науковий та клінічний інтерес у багатьох галузях. У нейрології, з моменту впровадження інноваційних та неінвазивних пристроїв, таких як стимулятор мозку, дослідження кортикальних процесів та їх нейронної основи відіграє фундаментальну роль.

Крім того, увагу нейрологів привертає застосування терапевтичних методів для лікування потягу до їжі. Цей описовий огляд має на меті пояснити зростаючий і постійний інтерес до проведення нейрологічних експериментів у сфері неінвазивної транскраніальної стимуляції.

Матеріал та методи. Після вступної частини, що пояснює історичну еволюцію неінвазивної стимуляції головного мозку (NIBS); ми спробуємо надати огляд двох методів стимуляції — транскраніальна магнітна стимуляція та транскраніальна стимуляція постійним струмом (TMS і tDCS); ми опишемо різні типи стимуляції, які можуть бути виконані із застосуванням цих методів, ефекти збудження/пригнічення, а також різні механізми дії на рівні активності головного мозку.

Результати. Ми також надаємо деякі пояснення щодо наслідків фасилітативного/інгібіторного ефектів і того, як ці методи стимуляції можуть бути використані для поглиблення знань з нейрофункціональної організації головного мозку.

Висновки. Результати дослідження показали вплив нейромодуляції головного мозку на заняття спортом та харчування.

Ключові слова: неінвазивна стимуляція головного мозку (NIBS), транскраніальна магнітна стимуляція (TMS), транскраніальна стимуляція постійним струмом (tDCS), кортикальне збудження, потяг до їжі.

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